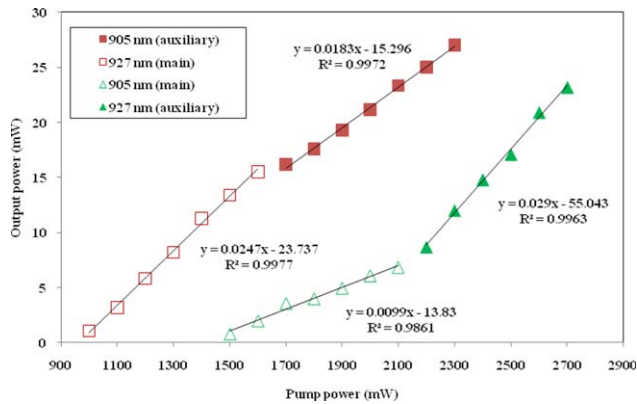


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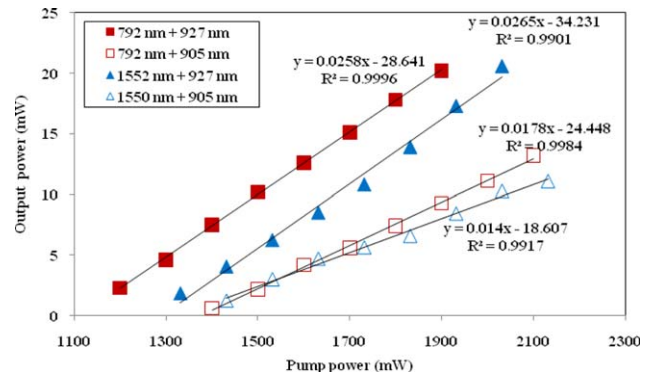


**Figure 2** The performance of the YDFL as another multimode pump is added as an auxiliary pump. [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Figure 1(a), 905 and 927 nm multimode pumps are used alternately as the main and auxiliary pump. Both pumps are injected into the inner cladding of the YDFL via a multimode combiner to create a population inversion and then amplified spontaneous emission which oscillates in the linear cavity to generate laser at the Bragg wavelength of 1901.6 nm. In Figure 1(b), a single mode pump of 792 or 1552 nm is used as the auxiliary pump while a multimode pump of 905 or 927 nm is used as the main pump. The output of the laser is tapped out from the cavity via the output port of the second FBG with 50% reflectivity. The output spectrum and power are measured by the OSA and power meter, respectively.

### 3. RESULTS AND DISCUSSION

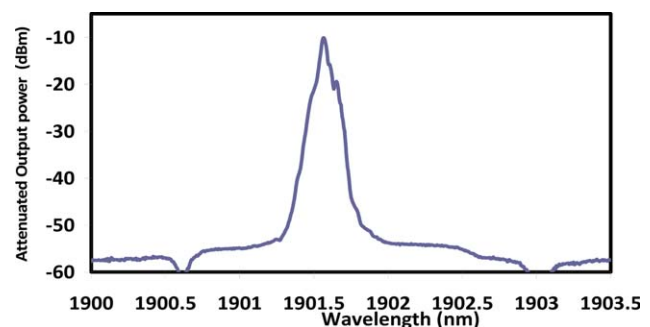
The performance of the proposed YDFL is first investigated with and without the auxiliary pump using two different multimode pumps of 927 and 905 nm according to the setup of Figure 1(a). Figure 2 shows the experimental result where the unshaded legends indicate the results of the lasers without the auxiliary pump. With 927 nm pumping, the YDFL has an efficiency of 2.47% with threshold pump power of 1000 mW. However, using 905 nm pumping, the efficiency drops to 0.99% and the threshold pump power increases to 1500 mW. This is most probably due to two main reasons; the first reason is the absorption/emission cross-section of the YDFL is slightly higher at 927 nm compared to the one at 905 nm. The second reason is the cavity loss is slightly lower at longer wavelength and thus the operation of the laser is more efficient with the use of 927 nm pump. To measure the effects of dual pumping on the efficiency and output power of the laser, a main pump is used to initiate lasing before launching of an auxiliary pump which help to increase the output power. First, 905 nm pump is used as the main pump alone and its power is increased from 1500 mW to the maximum level of 2100 mW. Then, the auxiliary 907 nm pump is launched and its power is increased every 100 mW to record six new readings until it max out at the total power of 2700 mW. From the graph, the efficiency is seen to improve by 1.91 to 2.90% with the incorporation of the auxiliary pump. As the 905 nm photons are inefficiently absorbed, the amount of excited Ytterbium ions is limited. When the 927 nm light is launched into the gain medium, more Ytterbium ions occupy the excited state thereby increasing the energy transfer process. Therefore, the population of Thulium ions at the upper state level also increases, and hence the laser efficiency improves. Conversely, by adding 905 nm pump as auxil-



**Figure 3** The performance of the YDFL as another single mode pump is added as an auxiliary pump. [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

iary pump for 927 nm pumped YDFL, the efficiency of the laser slightly reduces from 2.47 to 1.83%. This is most probably due to the saturation of the  $\text{Yb}^{3+}$  ions absorption at 927 nm as the 905 nm pump was turned on [14]. This reduces the energy transfer to the  $\text{Tm}^{3+}$  ions as the 905 nm pump power increases. However, the overall output power obtained is still better in this 927/905 nm combination pumps compared to that the previous combination of 905/927nm.

Figure 3 shows the experimental results obtained by the proposed YDFL of Figure 1(b) where another dual-pumping scheme combining a multimode and single mode pump is implemented. First, the performance of the YDFL is investigated when a single mode 1552 nm is added in the cladding-pumped fiber laser. For this experiment, a fixed 1550 nm pump power of 32 mW is launched into the system before we start increasing the power of the multimode pump. As shown by the blue shaded triangle legend in Figure 3, when the 1550 nm pump is coupled with the 927 nm source, the laser is generated at 1.9  $\mu\text{m}$  at the threshold pump power of 1332 mW with an efficiency of 2.65%. The efficiency was improved by 0.18% as compared to the result of using 927 nm laser diode alone as a pump source. By combining 1550 nm single mode pump with 905 nm multimode pump, the efficiency of the laser increases by 0.41% from 0.99 to 1.40% with laser threshold at 1400 mW as shown by the unshaded triangle legend in Figure 3. It is found that the combination of single mode 1550 nm and multimode 927 nm pumps provides a better lasing operation compared to than the combination of 1550 and 905 nm pumps. This is due to the pump absorption by Ytterbium ions, which is higher at 927 nm than 905 nm. In addition to photon absorption donated by Ytterbium



**Figure 4** The attenuated output spectrum for the proposed laser. [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

ions, 1550 nm incident pump increases the ground state absorption of Thulium ions caused by higher population inversion in the upper laser level.

In another experiment, 792 nm single mode pump is used as the auxiliary pump instead of 1552 nm pump. Similar to the previous experiment, a fixed 792 nm pump power of 200 mW is launched into the system before we start increasing the power of the multimode pump. As compared to the previous 1552 nm pumping, the efficiency of this laser was higher and the threshold was lower. By combining 905 and 792 nm pumps, the lasing efficiency was improved by 1.78% and the threshold was reduced to 1400 mW. As indicated by the shaded square legend in the figure, combining 927 and 792 nm pumps produces an even better lasing output with relatively higher efficiency up to 2.58% and a lower threshold pump power of 1200 mW. This is due to the 2:1 cross relaxation that occurs in the fiber which allows a large number of thulium ions to occupy the upper laser level of  $^3F_4$  thus, improving the laser efficiency.

It is found that the best efficiency of 2.9% and the highest output power of 27 mW are obtained by combining 927 nm pump with 905 nm pump. Figure 4 shows the attenuated optical spectrum recorded by an OSA for the proposed laser. It operates at 1901.6 nm, which coincides with the center wavelength of both FBGs with a signal to noise ratio of more than 40 dB. The 3 dB bandwidth is measured to be less than 0.02 nm and is limited by the OSA resolution. The best combination of pumps is 200 mW of 792 nm pump with 1700 mW of 927 nm pump, where only a total pump power of 1900 mW is required to generate 20 mW of 1.9  $\mu$ m laser output. As a comparison, the use of 1600 mW of 927 nm pump and 300 mW of 905 nm pump only produces 19.3 mW of output power.

#### 4. CONCLUSION

A series of dual-pumping schemes are proposed to improve the lasing efficiency of YTDFL based on a newly developed double-clad YTDF with a linear cavity. The highest efficiency of 2.9% is obtained at the highest output power of 27 mW by combining 905 nm with 927 nm multimode pumps. Compared to a 927 nm singly pumped YTDFL, about 0.43% increment is observed with no evidence of rollover at the highest output power. The use of single mode pumps of 1550 and 800 nm as a secondary pump also improved the performance of the laser. The best combination of pumps is 200 mW of 792 nm pump with 1700 mW of 927 nm pump where only a total pump power of 1900 mW is required to generate 20 mW of 1.9  $\mu$ m laser output.

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## SWITCHABLE DUAL-WAVELENGTH SINGLE-LONGITUDINAL-MODE ERBIUM-DOPED FIBER LASER BASED ON A THIN-CORE FIBER COMB FILTER AND SATURABLE ABSORBER

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**ABSTRACT:** A tunable dual-wavelength single-longitudinal-mode erbium-doped fiber laser using thin-core fiber comb filter (TCFCF) and a saturable absorber is proposed. TCFCF is achieved by splicing a thin-core fiber between two single-mode fibers. Two lasers incurred shifts of 1 and <3 pm, and corresponding 3-dB linewidths are 3.4 and 3.0 kHz, respectively. © 2015 Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 57:287–292, 2015; View this article online at [wileyonlinelibrary.com](http://wileyonlinelibrary.com). DOI 10.1002/mop.28826

**Key words:** dual-wavelength erbium-doped fiber laser; single-longitudinal mode; thin-core fiber comb filter; saturable absorber

#### 1. INTRODUCTION

Dual-wavelength fiber lasers have attracted much attention due to their wide range of applications in areas such as optical fiber